

# Team Efficiencies Within a Model-Driven Design Process

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**Abstract.** (Smith & Koenig 1998) formulated a model-based design process describing a triad of people, process, and technology (PPT) within an aerospace culture. It suggested that the time required for an organization to change to a new approach is a function of a minimum development time and powerful forces acting in tension (Lewin 1951).

(Wall et al. 1999) described the object model-based system, addressed the team dynamics involved in developing the products of the process, and proposed metrics to assess productivity of each team.

This paper examines the PPT triad at the lowest level, the minimum product cycle time. It shows that team interventions, above and beyond team productivity considerations, can produce even lower product cycle times.

A model shows the effect of the three components of the triad acting together. The lower cycle times possible are a product of team effects and technology advances in producing an individual object.

## INTRODUCTION

Using a model-based process consisting of objects, this paper describes the importance of team behavioral optimization (TBO). It expands upon an earlier paper (Wall et al. 1998), which described in detail an object-based system of models being used at the Jet Propulsion Laboratory (JPL) to produce real, coherent hardware and software products. JPL is responsible for the planetary missions of the NASA strategic plan.

Three unique teams interact to resolve incoherences in relationships among objects. Each team is scripted for effectiveness and conducts sessions resulting in changes to the objects. The top set of objects contains the overall requirements, while

the lower sets contain the design.

Since the object model-based process is fractal (Taylor 1995), concurrence is achieved by resolving interfaces and attributes among objects. The method involves conversations within and across three primary teams: mission team (A), design team (B), and test team (C). Each team is composed of experts and project personnel with individual motives as well as a common mission. Team efficiency is a function of how fast the team can resolve design issues as objects are being developed (Wall et al 1999).

Designing, developing, and testing each object concurrently decreases cycle time. (Smith & Koenig 1998) implied that a basic object typical of the aerospace mission culture could be produced in about five months. Using this number as the average object creation time, this paper proposes a mission system time constant, based on five metrics.

Because the process involves three teams of engineers who resolve design issues among the object models, team behavioral optimization (TBO) is essential. This paper suggests a method to identify relevant TBO interventions and to measure their impact. TBO interventions create forces – for example, dissonance (Festinger 1957) and motivation toward teamwork (Schein 1999) – to compensate for individual forces that oppose effective team function.

## OBJECT MODEL-DRIVEN SYSTEM DESIGN

The fifth principle described in (Smith & Koenig 1998) uses a dynamic system engineering process, a top down system approach to the iterative team/model process design. This, combined with the next two principles, concurrency and model-driven design, involves an intimate relationship between technology and teams. (Cummings & Worley 1993) stated that sociotechnical systems (STS) theory has

two basic premises. Of interest here is the first, that effective work systems must jointly optimize the relationship between their social and technical parts. In order to effect their integration, it is necessary to examine the state of readiness of the computational technology and tools, then integrate the social order of teams with the appropriate supporting system.

The best tools for STS integration are ones that support conversation rather than analysis. Sophisticated simulation analysis tools available to each team member operate in the background to support the main activity. Pertinent data is distilled from the analysis tools and organized in a conversational database.

Because simulations relate to each other by process, they can provide an integrating function for Hammer's (Hammer 1996) concept of a process – centered organization. Figure 1 shows a grouping of the major simulation tools by the Mission and System Design (MSD) and Design, Build, Assemble, and Test (DBAT) processes. The Verify, Integrate, Validate and Operate (VIVO) process integrates and tests the ensemble.

These processes, a collection of like tasks and activities, are not prescriptive. Within each process, teams establish their own behavioral processes and practices, uniquely suited to the team members involved.

Each process contains subsystem objects, and

each object can be decomposed into fundamental objects within CAD tools. Each object is a nested waterfall of design, development, and test. Requirements are maintained only at the highest level. The design itself of the lower objects, therefore, is consistent with the system requirements (Taylor 1995). It is essential that these objects maintain relationships with each other that are relevant and relative to the higher level requirements.

Computational technology supports this system of objects in two distinct ways. First, it provides object models to create a virtual environment that captures, verifies, and even tests interactions of requirements. These models are found within the MSD process. Second, it tests and verifies the logical designs of circuits and software prior to hardware and software production. Abid et al. (1998) referred to this as 'hardware/software co-design for embedded systems.' These models are contained within the DBAT process.

This paper establishes some minimum time estimates for the creation of the two basic object models, MSD and DBAT, and postulates that the design time is the adjudication of these objects within and across the system of teams.

Recently at JPL, Edward H. Kopf took a practical, flight-qualified design through the co-design process, beginning with i-logic's Statemate (development tool) to a Flight Programmable Gate Array (FPGA). The constraints of flight qualification

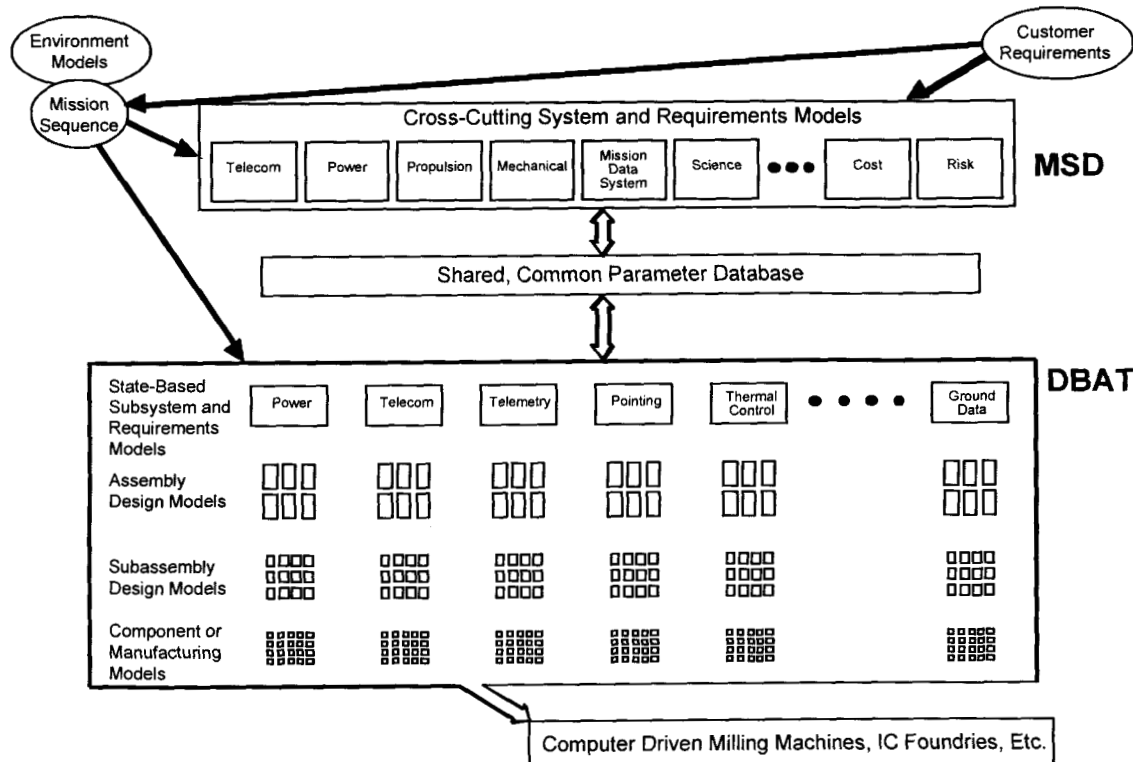


Figure 1. Model Architecture

and reliability for NASA's X-33 increased the difficulty tenfold. To avoid confusing the synthesis tools and producing unnecessarily complex hardware, he designed a simplified instruction set, a breakthrough to developing qualified hardware/software design. Using this simplified set, a basic object requires about five months to produce. A subsystem team is expected to take about twice as long. Therefore, a vertical integration factor of two is assumed.

Co-design begins with detailed design, captured by design models, and extends to CAD systems. Connecting this process to other kinds of virtual models creates a top down virtual manufacturing system of objects reassembled by the VIVO process.

(Wall et al. 1998) described JPL's implementation of modeling system requirements for space missions. This paper is unique in its complete description of a 'Top Down' system design process which creates dialogues on technical issues and uses the technology (shared, common parameter database) to manage the information flow.

Combining these two model types with a team approach enables integration of teams, processes, and tools. Figure 2 describes generic team conversations across design processes. First, Team A (the mission team) constructs self-verifying requirements models

(Baker 1997). Technical conversations include performance evaluations and critical design tradeoffs. If the design parameters,  $p$ , exceed the requirements,  $P$ , Team A decides whether to alter requirements,  $P$ , or flight sequences,  $S$ . For this level of conversational/ model environment to work, models must be kept simple and distinct. (Barbieri & Estabrook 1997) reported that a simple model (Nuthena's Foresight tool) can be constructed in about one month.

Team B (the design team) constructs detailed object design models, checks for and evaluates requirements incoherence, and reports its subsystem recommendations to Team A. Team A either accepts Team B's recommendations, changes the requirements, or changes the flight sequence. The margin of available resources determines whether alternative design suggestions are used.

Team C initially tests model objects, then tests actual hardware and software. Team C also uncovers requirements' incoherence. After test evaluations, it reports results to Team B. If results are unexpected, Teams B and C attempt to clarify the issues before reporting to Team A. In this system, data flows from top to bottom, from upper level models to designs, and information returns through a sequence of interacting Teams A, B, and C.

Team A adopts the role of direction and, thus, decides on the correct course, given project commitments. Team B provides design possibilities, and Team C evaluates the results. All teams provide input necessary to iterate the design toward hardware and software maturity.

Thus, the innovation is a model-driven system designed for compatible interface with teams. The models themselves provide documentation of the design and faster information exchange. These models, with their carefully designed object relationships, provide the tool counterpart to relationships among teams.

Referring to Figure 2, three basic metrics emerge. All are efficiency factors. All are relative, integral time measures with the shortest time interval,  $f_m$  as the base. Thus,  $f_m$  represents the basic unit time factor (normalized) involving the mission characteristics.

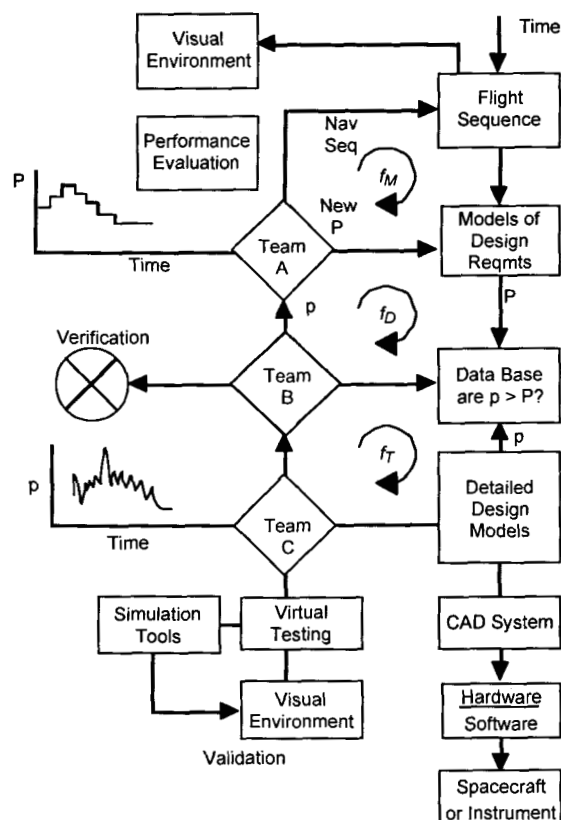
$$f_m = No/r \triangleq 1 \quad (1)$$

$$f_d = x_0 f_m$$

$$f_T = x_1 f_m$$

where  $r = \# \text{ issues/time}$

and  $No = \text{Number of issues}$



**Figure 2. Team Conversations versus Design Process**

The second,  $f_d$ , represents the design process, and the third,  $f_T$ , represents the test loop. The three factors are integral time measures of the rate at which

incoherences are resolved. For example,  $f_d$  is the integral time factor required to resolve design issues by Team B. To determine  $f_d$ , one measures total time to resolve design issues. A rate and, thus, team efficiency can be determined if the total number of design issues is tracked. Team efficiency is a measurable quantity of how well the team interacts to resolve design issues. In this case,  $f_d$  is nearly twice  $f_m$ .

Interventions in team dynamics are aimed at optimizing efficiency.

### MODEL

A model of the process described in Figure 2 can be constructed to directly relate people, processes, and tools. The model for projects producing similar products within any company is one of a dynamic system, with product teams operating at natural harmonic frequencies. A useful dynamic representation of such product team process is that of a system of vibrating membranes in equilibrium.

In this representation, the inertial forces are the team dynamic forces in action. These forces represent the inertial mass of the membrane in tension. The tension force is the infrastructure of the environment. Therefore, the phase velocity of the membrane is the square root of the tension force divided by the inertial mass of the system. From the differential equation, the displacement of the membrane is a harmonic Bessel function with a natural frequency proportional to the ratio of these forces.

It is of interest to study changes to the system's equilibrium state in order to reduce overall product development time.

### FORCE-FIELD ANALYSIS

One way to conceptualize change to an equilibrium state is through manipulation of force fields (Lewin 1951). A product team's cycle time is a function of a field of forces balanced in tension. Opposing forces produce a characteristic equilibrium state (vibrating harmonic) or product development time. This force field is the product of the cultural environment and is unique to each organization. Sub-cultural forces (Schein 1997), creating a dynamic tension not easily changed, work to sustain equilibrium.

There are two ways to change systemic cycle time. One method is to modify the environment and tools in the system. Experience has shown this to be of marginal value alone, though it might affect individual efficiency. Another method is to decrease the resultant equilibrium forces by direct management action on the product development team (e.g., Schneider 1994; Simons 1995).

Compelling forces on the team (compellers) constrain change (add mass to the system membrane). These are the resultants of previous drivers, forces that maintain the status quo, and restrainers, forces opposing drivers. This is an adaptation and expansion of (Lewin 1951), which states that equilibrium in any system or organization is reached as the resultant of opposing driving and restraining forces. The system maintains equilibrium in the absence of opposing forces. Thus, identifying and manipulating the field of forces to move the system's equilibrium point in one direction or another can effect change in an organization.

Decreasing constraining forces, according to the membrane model, would effectively decrease the

Table 1. TBT Data Summary

Rating	Commitment	Goals/objectives	Leadership	Creativity	Growth	Accountability	Trust	Participation	Feelings Expressed	Good Listening	Clear Decision Method	Self Assessment
1	8%	0%	3%	0%	4%	4%	0%	0%	8%	2%	0%	14%
2	6%	3%	14%	3%	8%	4%	9%	0%	0%	4%	0%	8%
3	0%	6%	11%	3%	13%	8%	0%	8%	0%	13%	0%	11%
4	19%	20%	25%	19%	33%	13%	9%	8%	17%	21%	0%	33%
5	28%	17%	22%	28%	25%	25%	17%	42%	42%	33%	42%	19%
6	33%	31%	17%	36%	17%	29%	57%	42%	25%	27%	42%	11%
7	6%	23%	8%	11%	0%	17%	9%	0%	8%	0%	17%	3%
Mean	4.8	5.4	4.3	5.3	4.2	5.0	5.4	5.2	4.9	4.6	5.8	3.8
Mode	6	6	4	6	4	6	6	5/6	5	5	5/6	4

membrane mass and, thus, reduce product development time. Management can intervene by introducing forces opposing compellers (impellers) and thus reduce cycle time. Two examples of impellers relevant to this paper are the institutionally supplied and supported process interventions (for example, MSD, DBAT, VIVO) to sustain the team working environment and the Team Behavioral Tool (TBT), which gives the team direct feedback on its functioning via its own input. Both of these forces are impellers aimed at optimizing team productivity.

The outcome of appropriate interventions to optimize team function is TBO. Process pressure is organizational direction toward common processes and cultural pressure toward consensus. TBO interventions appropriate to each team are defined by the team's response to its own Team Behavioral Tool (TBT), uniquely developed by the team and facilitators to fit the team's particular needs. The TBT is a collection of Likert-scaled statements that, in the team's opinion, describes its own optimal functioning. At the conclusion of team process, each team member responds to the items by indicating degree of agreement with each statement on a scale from one to seven (Likert 1961). Input data is gathered at a central database and summarized for feedback to the team and team leader. Direction of responses, which are clustered into 12 categories, indicates needed team leader intervention (see Table 1).

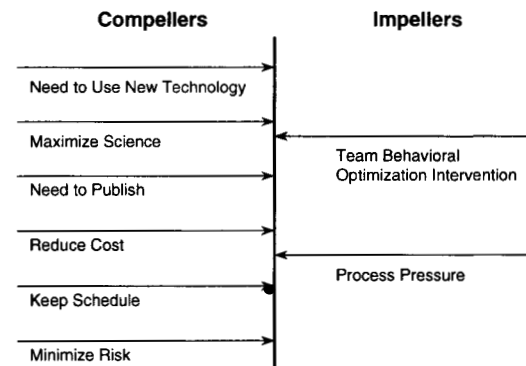
After baseline, team leaders are trained, as needed, to intervene effectively and immediately with their teams to remove deficiencies in optimal functioning as quickly as possible. Over time and repeated team sessions, the data is used to determine the impact of interventions on team cycle time.

The TBT is a living tool amenable to modification by team consensus when items no longer pertain or new items are needed to describe optimal function.

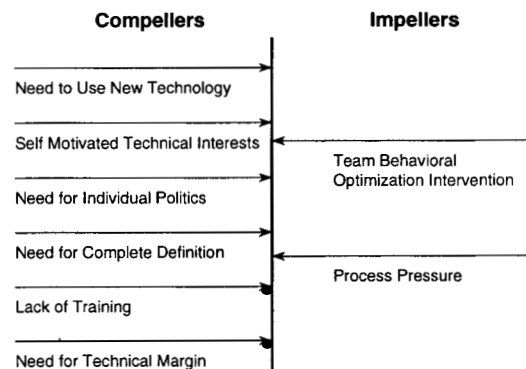
In the following model, all forces are regarded as equal in magnitude. Compellers, taken together, represent a previous equilibrium state. Impellers represent forces pushing change from that previous equilibrium state. These forces oppose each other and alter the equilibrium state to a new characteristic harmonic vibration.

Because changes to organizational culture take time (Schein 1997), one can describe the movement from one equilibrium state to another with this type of model. If more rapid movement is needed, appropriate intervention can be applied. Some interventions – for example, those aimed at improving product quality – can decrease team efficiency and, thus, may require offsetting impeller actions.

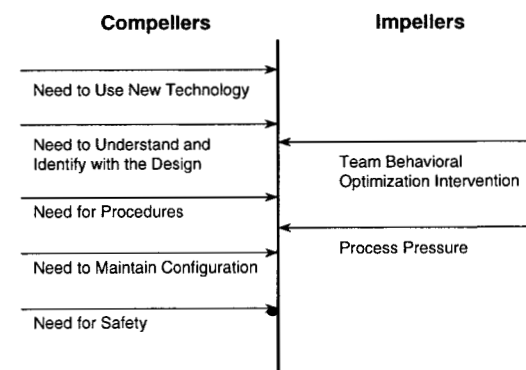
Models of the dynamic tension between compelling and impelling forces within product development teams (for example, the process described in Figure 2) are shown in Figures 3, 4, and 5. Compellers and impellers are forces believed to affect the dynamics of team performance. For example, mission product development time will remain constant under the constant field forces represented by the compellers of Figure 3. Change to this system can occur when management intervenes to reduce cycle time. Impellers to optimize process and to increase team efficiency are illustrated.



**Figure 3. Mission Team Dynamic Forces**



**Figure 4. Design Team Dynamic Forces**



**Figure 5. Test Team Dynamic Forces**

Assuming conservation of momentum during the changes of the process, the new cycle time a team with these two impellers is given by,

$$f'_{(PDT)} = f_{(PDT)} \cdot \frac{\sum_i^L (CF_i - IF_i)}{\sum_i^L CF_i} \quad (2)$$

Where  $f_{(PDT)}$  is the product of the current integral time of the product development team process and the ratio of the team dynamic field forces.

Each team process defined at JPL is altered in roughly the same way because impellers represent changes to the organizational culture. The development of a team tool itself is a cultural intervention, even prior to its actual implementation. All actions are designed to reduce cycle time.

Given the 'drum' model of the dynamic actions of each product development team, one can construct an overall model of a new product cycle time, in terms of the present equilibrium state to see the effect of these interventions. In Equation 3, this new state is the minimum cycle time,  $\tau_{min}$  to be expected. It is a function of the vertical design time,  $f_V$  inflated by the vertical team integration effect, and multiplied by the horizontal team effects. The horizontal team effects are the sum of each of the dynamic systems described above, multiplied by a concurrency factor,  $\eta_c$ .

At the present time, JPL is producing missions with a concurrency factor of about 50 percent, estimated from a Venus orbital study (Smith 1998). A vertical efficiency integration factor of nearly two, estimated by subsystem personnel, offsets this savings, and is difficult to reduce.

Based on this linear description of the compellers versus impellers acting equally, a minimum time in months,  $\tau_{min}$ , can be calculated from Equation 3, using the efficiencies estimated in Figure 6, and the constants of equation 3.

These results show that effective team optimization interventions can reduce team cycle time by several months. Figure 6 shows representative factors increasing with complexity of the team task for each of the three teams, the test team being the most difficult of the three. For example, test team cycle time is three times that of mission team cycle time. For purposes of this discussion, it is assumed that the technology factor remains constant at five months, with a vertical team integration factor of 2.

With no impellers in the system, the compellers maintain system equilibrium as only potential forces,

and the equation becomes the product of the sum of the three factors and the technology term,  $\tau_{obj}$  times the vertical integration factor. Thus, model-based process and technology alone reduce cycle time to 30 months. This represents a 38 percent decrease over Pathfinder, which was 48 months.

$$\tau_{min} = \left[ f_M \frac{\sum_i^L (CF_i - IF_i)}{\sum_i^L (CF_i)} \right. \quad (3)$$

$$+ f_D \frac{\sum_j^M (CF_j - IF_j)}{\sum_j^M (CF_j)}$$

$$\left. + f_T \frac{\sum_k^N (CF_k - IF_k)}{\sum_k^N (CF_k)} \right] \cdot \tau_{obj} \cdot f_V \cdot (1 - \eta_c)$$

$f_M$  = cycle time factor in resolving mission issues

$f_D$  = cycle time factor in resolving design issues

$f_T$  = cycle time factor in resolving test issues

$CF_i$  = Compeller Forces, weighted equally

$IF_i$  = Impeller Forces, weighted equally

$\tau_{obj}$  = cycle time to develop the basic object  
≅ 5 months

$f_V$  = vertical team integration ≅ 2

$\eta_c$  = concurrency factor ≅ 50 percent

$\tau_{min}$	$f_M$	$f_D$	$f_T$	$CF_i$	$IF_i$	$CF_j$	$IF_j$
30	1	2	3	6	0	5	0
19	1	2	3	6	2	5	2

Figure 6. Minimum Cycle Time

Assuming the vertical team efficiency cannot be reduced significantly, because of the other factors (e.g., parts acquisition), this analysis shows that application of the impellers, TBO interventions and process pressures can reduce cycle time to approximately 19 months, the original goal of the reengineering team, even with the present state of concurrency. This represents another reduction in cycle time of 37 percent.

The importance of the compellers and impellers in Figures 3, 4, and 5 will be validated using measurements of team process and behavioral optimization. Without continual team building, these efficiencies will deteriorate to original values.

## MEASUREMENT

The model requires five measurements. First, efficiency factors measure time to resolve technical issues and update the system models. These represent the design process. Averages of time to resolve issues are taken over a period to account for expected variances due to issue complexity. This interval should enable maintenance of quality records. Beginning attempts will assume quarterly averages to be adequate.

Second, the coefficient value -- object development, design, and test time of five months -- represents the technology component. This factor should always be compared to the investment cost made in tools. Third is the vertical team efficiency factor, also an averaged value to account for complexity. Fourth is the concurrency factor, which measures the concurrency of the processes themselves. These metrics are required to continually monitor the model-driven system.

The fifth measurement is people in teams. An adaptation of Lewin's field system model is shown in Figures 3, 4, and 5 above. As indicated, the mission team is driven by compelling forces to obtain relevant science. People on the design team are individually motivated by technology and independent pursuits. The test team is strongly compelled to produce reliable results in order to validate the design.

The most difficult to measure of the five factors is the people component. Drawing from Lewin's field theory, opposing compelling forces are two types of impellers. As mentioned earlier, one is the pressure toward common process and consensus. The second is a cluster of impellers representing optimal team performance and work satisfaction (e.g., Cranny et al. 1992; Jankowicz 1998; Nadler & Lawler 1989). To capture the second impeller via these constructs in an easily administered form that requires minimal team time, each team develops its unique TBT. This tool enables the team to self-monitor its behavioral functioning and the team leader to pinpoint specifically needed team building interventions to optimize it. This innovates standard

team building by eliminating unneeded steps and focusing only on issues deemed important to the team.

Baseline values of 12 categories of statements (see Table 1) are compared continuously to weekly response averages. These measures are statistically analyzed to determine their relation to ongoing team building activities and their correlation with design process cycle times.

The Team Climate Inventory (Anderson and West 1998) is administered to each team member once monthly. Results are correlated with results of the TBT and with design cycle times.

## CONCLUSIONS

This paper presents a model of design cycle time which includes three factors -- people, process, and technology. Impelling forces are used to analyze the people factor. It is shown that team optimization can offset individual motives and thus reduce overall cycle time by another 37 percent. Three teams concurrently engaged in a model-driven system of space mission design and development are optimized to minimum cycle time.

The essential people component has been overlooked, possibly because technology and design process are easier to address. Nevertheless, NASA's goal of reducing development cycle time of space missions by a factor of two cannot be realized without consideration of the people element.

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